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The mirroring hypothesis: theory, evidence, and exceptions

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Abstract

The mirroring hypothesis predicts that organizational ties within a project, firm, or group of firms (e.g., communication, collocation, employment) will correspond to the technical dependencies in the work being performed. This article presents a unified picture of mirroring in terms of theory, evidence, and exceptions. First, we formally define mirroring and argue that it is an approach to technical problem-solving that conserves scarce cognitive resources. We then review 142 empirical studies, divided by organizational form into (i) industry studies, (ii) firm studies, and (iii) studies of open collaborative projects. The industry and firm studies indicate that mirroring is a prevalent pattern but not universal. However, in technologically dynamic industries, partial mirroring, where knowledge boundaries are drawn more broadly than operational boundaries, is likely to be a superior strategy. Firms can also strategically 'break the mirror' by implementing modular partitions within their boundaries, or by building relational contracts across their boundaries. Finally, studies of open collaborative projects, most of which focused on software, were not supportive of the hypothesis. We argue that digital technologies make possible new modes of coordination that enable groups to deviate from classical mirroring as seen in firms.

JEL classification: D23, D85, L22, O32

1. Introduction

Innovation is a process in which people define problems and then actively develop new knowledge to solve them (Nonaka, 1994). In the modern economy, much new knowledge takes the form of new product and process designs. Modern efforts to develop new designs in turn require the coordination of an ever wider range of disciplines, embodied in complex technical systems and processes (Brusoni *et al.*, 2001).

Given the well-known challenges of coordinating complex interdependent tasks (e.g., Thompson, 1967: Galbraith, 1974), theorists have tended to predict (or recommend) that the formal structure of an organization will (or should) "mirror" the design of the underlying technical system (e.g., Conway, 1968; Henderson and Clark, 1990; von Hippel, 1990; Chesbrough and Teece, 1996; Sanchez and Mahoney 1996; Baldwin and Clark, 2000). These theories in turn lead to empirically testable predictions: the organizational ties in a project, firm, or group of firms (e.g., communication, collocation, employment relations) will (or should) correspond to the technical dependencies in the work being performed.

This basic idea has different names in different fields. In organization design, it can be seen as an application of task contingency theory to complex technical systems (Lawrence and Lorsch, 1967; Thompson, 1967; Galbraith, 1974; Tushman, 1979; Drazin and Van deVen, 1985; Tushman and Nadler, 1978). In computer science, it is known as Conway's Law (Conway, 1968). Notably, the hypothesis predicts correspondence but does not impose a direction of causality: effects may flow from organizational structure to technical design (Henderson and Clark, 1990); from technical design to organizational structure (Chandler, 1977); or in both directions (Baldwin and Clark, 2000; Fixson and Park, 2008).

A thorough understanding of the evidence for and against the mirroring hypothesis is difficult to achieve. The relevant literature is scattered across a number of fields in management, economics, and engineering, and there are significant differences in how the hypothesis is interpreted in the different streams of literature. This article seeks to present a unified picture of the mirroring hypothesis in terms of theory, evidence, and exceptions. Accordingly, this study makes two contributions. First, it formally defines the mirroring hypothesis and systematically reviews and summarizes the empirical evidence pertaining to it. Second, it synthesizes observations from a wide range of studies to describe the boundary conditions of mirroring, that is, when and why mirroring is likely to be an effective strategy vs. when and why organizations can benefit by 'breaking the mirror' partially or wholly.[1]

Our analysis proceeds as follows. First, we trace the intellectual roots of the mirroring hypothesis, formally define it in terms of network graphs, and work out its descriptive and normative implications. We argue that the mirroring of technical dependencies and organizational ties is an approach to organizational problem-solving that conserves scarce cognitive resources.

Building on this theoretical base, we then systematically review the empirical evidence pertaining to the hypothesis. We consider 142 empirical studies, most of which were published between 2000 and 2015. The studies were categorized according to whether they were primarily descriptive (seeking to establish relationships between technical dependencies and organizational ties) or normative (considering the performance of mirrored or unmirrored organizations) and further divided by organizational form into (i) industry studies, (ii) firm studies, and (iii) studies of open collaborative projects. We then classified each study according to whether its results fully or partially supported or failed to support the mirroring hypothesis.

The industry and firm studies showed that correlation between technical interdependencies and organizational ties is a common pattern both cross-sectionally and over time. Over two-thirds (70%) of the descriptive studies provide strong evidence of mirroring, 22% provide partial support, while only 8% do not support the hypothesis. The normative studies of firms provide a more nuanced view of the phenomenon. In particular, they reveal the existence of a mirroring 'trap': firms focused on the current technical architecture may fall victim to architectural innovations arising outside their boundaries. Thus, in technologically dynamic industries, partial mirroring, where knowledge boundaries are drawn more broadly than operational boundaries, is likely to be a superior strategy. Furthermore, it is possible for firms to strategically 'break the mirror' in two ways: first, by implementing modular partitions within their own boundaries; and second, by building relational contracts that support high levels of technical interdependency across their boundaries. Strategic mirror-breaking can be a source of competitive advantage and over time can change the structure of industries.

The evidence from open collaborative projects (a relatively new form of organization) paints a very different picture. Here the majority of descriptive studies (56%) *do not* support the mirroring hypothesis, while normative studies are too few in number to be decisive. We will argue that these contradictory results arise because digital technologies make possible new modes of coordination that enable groups to deviate from classical mirroring as seen within firms.

Section 2 presents the theory behind the mirroring hypothesis and formulates it in descriptive and normative terms. Section 3 describes our sample and methods of analysis. Section 4 presents an overview of our results. (Our detailed findings are summarized in two Supplementary Appendices.) Sections 5–7 describe themes that cut across descriptive and normative formulations. Section 8 summarizes our findings, describes boundary conditions, and concludes.

1 Throughout the article, we place single quotation marks around terms we use as metaphors and double quotation marks around direct quotes from the work of others.

2. What is the mirroring hypothesis?

The management literature that pertains to the mirroring hypothesis commonly draws on two distinct sources for its motivation: (i) the literature on organization design and organizations as complex systems (e.g., Thompson, 1967; Galbraith, 1974; Weick, 1976); and (ii) the literature on product design and products as complex systems (e.g., Alexander, 1964; Parnas, 1972, 1978; Ulrich, 1995). A separate tradition in computer science builds upon "Conway's Law," which states that "organizations which design systems … are constrained to produce designs which are copies of the communication structures of these organizations" (Conway, 1968: 31). All three traditions make use of the concept of modularity.

Scholars in the organization-design tradition usually attribute the concept of modularity to Herbert Simon (1962, 1981), who used the parable of Hora and Tempus to illustrate the advantage of partitioning a complex problem into parsimoniously linked sub-problems:

> Hora … put together subassemblies of about ten elements each. … Hence, when Hora had to put down a partly assembled watch…he lost only a small part of his work, and he assembled his watches in only a fraction of the man-hours it took Tempus. (Simon, 1981: 188)

By partitioning the watch into modular subassemblies, Hora made it easier to cope with the complexity of creating a watch. Thompson (1967) went on to argue that, to achieve efficiency in the face of underlying complexity, organizations should place "reciprocally interdependent" tasks within a common organizational group.

Scholars in the product-design and computer science traditions take inspiration from Simon, but also refer to works by Alexander (1964) and Parnas (1972, 1978). Like Simon, Alexander (1964) argued that it is easier to cope with the complexity of a large-scale problem if it is decomposed into parsimoniously linked sub-problems. Parnas (1972, 1978) argued that it is easier to split development work across a group if people can work independently and in parallel. To support parallelism, Parnas encouraged developers to avoid sharing assumptions and data. Specifically, he contended that every developer's task assignment should lie within a product module that is "characterized by its knowledge of a design decision that it hides from all others" (1972: 1056).

Information hiding as a means of controlling complexity is a fundamental principle underlying the mirroring hypothesis. With information hiding, each module in a technical system is informationally isolated from other modules within a framework of system design rules. This means that independent individuals, teams, or firms can work separately on different modules, yet the modules will work together as a whole (Baldwin and Clark, 2000). As a result, there will be a mapping[2] from technical modules to designers or design teams (Conway, 1968; Parnas, 1972, 1978). This mapping allows the mirroring hypothesis to be formally stated in terms of a structural correspondence between two networks, one technical and one organizational.

2.1 Formal definition

Following Simon (1981), we define the elementary components of a technical system as a set of decisions and/or tasks. If the system is a design, the tasks are decisions about design parameters (Baldwin and Clark, 2000). However, more broadly, the components of a technical system include all the tasks and decisions required to design, operate, and maintain the system (Baldwin, 2008; Arthur, 2009; Puranam *et al.*, 2012). Examples of technical systems include complex products and services, large software systems, manufacturing processes, supply chains, systems for transport and logistics, military systems, the electrical grid, telecommunication networks, and the Internet. Technical systems are often combined to make larger systems as when a handset, software, and the telecommunication network are combined to create the functionality of a mobile phone (Arthur, 2009).

The *technical architecture* of a system captures "what depends on what" as determined by the underlying technology. It is the scheme by which the technical system's functions and sub-functions are allocated to distinct components (nodes in a network), plus a description of the technical dependencies (links) between components (Ulrich, 1995; Baldwin and Clark, 2000; Whitney *et al.*, 2004). Technical dependencies are relationships of the form "if something in Component 1 changes, then Component 2 may need to change as well" (Parnas 1972, 1978; Baldwin and Clark, 2000).

2 The mapping is not one-to-one because a single designer or team may have responsibility for several modules. However, each module will have only one designer or design team (Conway, 1968, p. 30).

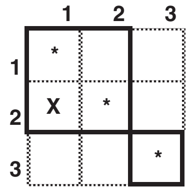

Figure 1. A technical dependency matrix.

The *division of labor* captures "who does what." It is the scheme by which the tasks in the technical architecture are assigned to people or teams (nodes) who will perform the tasks plus the organizational ties, such as communication channels, geographic collocation, or employment relations, that link those people.[3] The mirroring hypothesis posits that, in a complex system,[4] the technical architecture and the division of labor will "mirror" one another in the sense that the network structure of one will correspond to the structure of the other. To visualize what this means, we can represent the technical and organizational networks using matrices.

For the technical architecture, a *technical dependency matrix*[5] shows the network of dependencies among the technical components or tasks. For example, Figure 1 depicts a technical system with three tasks such that Task 2 depends on Task 1, and there are no other dependencies. The single dependency is recognized by placing an "**x**" in the column of Task 1 and the row of Task 2. The heavy lines in the figure group the tasks according to their dependencies.

The technical dependency matrix does not describe the division of labor nor methods of coordination. We introduce the *organizational ties matrix* for this purpose. This matrix is constructed by first associating a person or team with each task and labeling each cell on the main diagonal accordingly. For example, for the system depicted in Figure 1, suppose Alice is given Task 1, Bob is given Task 2, and Carol is given Task 3. In a separate 3×3 matrix with similar rows and columns, we place the uppercase letters A, B, and C along the main diagonal as shown in Figure 2. These assignments indicate which agents have primary responsibility and knowledge about each task. The mirroring hypothesis predicts that, given the dependency between their tasks, Bob and Alice will share one or more explicit organizational ties that enable them to coordinate their actions. We denote the (presumptive) presence of an organizational tie between Alice and Bob, by placing the notation "ab" in Alice's column and Bob's row. By comparison, Carol shares no task dependencies with Alice or Bob; thus, the mirroring hypothesis predicts no organizational ties for her. More generally, the mirroring hypothesis predicts that the technical dependency matrix and organizational ties matrix will have entries in the same cells. The structure of one will correspond to the structure of the other, as can be seen by overlaying Figure 2 on Figure 1.

What constitutes an organizational tie? Early theorists such as Simon (1962), Thompson (1967), and Conway (1968) mainly focused on communication links between people. However, actual communication is often transient and thus difficult to observe (Bucciarelli, 1994). Collocation of individuals is known to facilitate communication (Allen, 1984), and hence, it often serves as a proxy for the existence of a communication channel. Additionally, full coordination may require not only communication, but also cooperation and/or efficient methods of settling disputes (Williamson, 1975, 1991; Gulati *et al.*, 2005; Jacobides, 2006). People employed by the same organization may be more disposed to cooperate and are embedded in management hierarchies capable of making expeditious decisions. Thus, employment by the same firm is a third form of organizational tie, which can positively affect coordination of technical dependencies.

3 Tasks may be assigned to machines, but we are concerned with linkages between people. Thus we would define machine tending or management as person's task and look for organizational ties between people.

4 As discussed below, mirroring is basically a strategy for conserving cognitive resources of individuals and organizations. Simple systems are easily comprehended, thus do not need to be mirrored.

5 Technical dependency matrices are often called Design Structure Matrices or DSMs (Baldwin and Clark, 2000; Steward, 1981; Eppinger, 1991).

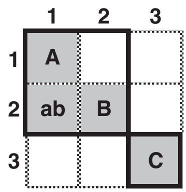

Figure 2. An organizational ties matrix (corresponding to the previous technical dependency matrix).

2.2 Mirroring as an approach to problem-solving

The mirroring of technical dependencies and organizational ties can be explained as an approach to organizational problem-solving that conserves scarce cognitive resources. People charged with implementing complex projects or processes are inevitably faced with interdependencies that create technical problems and conflicts in real time. They must arrive at solutions that take account of the technical constraints; hence, they must communicate with one another and cooperate to solve their problems. Communication channels, collocation, and employment relations are organizational ties that support communication and cooperation between individuals, and thus, we should expect to see a very close relationship—technically a homomorphism—between a network graph of technical dependencies within a complex system and network graphs of organizational ties showing communication channels, collocation, and employment relations. This in turn means that organizational ties will be dense within modules of the system where technical dependencies are dense and sparse across modules where technical dependencies by definition are sparse (Baldwin and Clark, 2000).

Aligning organizational ties with technical dependencies is an economical way to manage complex technical systems that require human coordination in real time. Notably, such alignment does not have to be a conscious choice by any one person or group, but can arise through an evolutionary process of decentralized problem solving (Alchian and Demsetz, 1972; Nelson and Winter, 1982). That is, the people charged with managing a complex technical system will create and/or eliminate technical dependencies and organizational ties where and when needs arise. If needs persist, the association between technical dependencies and organizational ties will also persist and the correlation will be observable.

Henderson and Clark (1990) were among the first to recognize that mirroring can arise through invisible organizational processes. They noted that "organizations are boundedly rational and, hence, . . . their knowledge and information processing structure come to mirror the internal structure of the product they are designing" (p. 27). They also found that mirroring could have negative consequences for performance, an issue we shall return to below.

Nickerson and Zenger (2004) viewed organizations as problem-solving entities, but saw the basic problem as opportunism, not complexity *per se*. They argued that solving complex problems with many interdependencies requires knowledge sharing (communication) among agents, but such exchanges are subject to opportunistic hazards in the form of appropriation (stealing) and accumulation (hoarding). Markets have a low capacity for remedying these hazards; thus, complex problems are best addressed within hierarchies, that is, by firms. Their reasoning implies that complex problems with many interdependencies will (or should) be addressed by agents with at least two organizational ties—communication links that permit knowledge exchange and employment by the same firm to dampen opportunistic behavior.

Puranam *et al.* (2012) advanced the theory of organization design by pointing out that there are different types of interdependence between technical components of a system. Information exchanges are valuable when one agent needs to predict another's action to choose his or her own best course. Such "epistemic" interdependence requires coordination, hence communication in near real time. Below, when we speak of technical interdependence, we specifically refer to epistemic interdependence. Epistemic interdependence creates a need for coordination, which is in turn facilitated by organizational ties.

2.3 Origins of the mirroring hypothesis

Different versions of the mirroring hypothesis were derived independently by James Thompson and Melvyn Conway at approximately the same time. There is no evidence that they knew about each other.

Building on Simon (1957), Thompson (1967) argued that, given bounded rationality, actors performing technologically interdependent tasks should be collocated and communicate more with each other than with actors outside their group. Furthermore, when interdependence is extensive so as to "overtax communication mechanisms," the organization should rank order the degree of interdependency among actors, let those with the greatest interdependency form a group, and cluster the smaller groups into "an overarching second-order group" (p. 59).

This method of clustering implicitly forms a hierarchy. Thompson went on to say that "if we assume that the probability of conflict among [actors] or groups is directly proportional to their degree of interdependence," then this hierarchical structure can serve as a device for the resolution of conflicts (*ibid.* p. 60). Thus, actors performing interdependent tasks should have the organizational ties of collocation, communication linkage, and a common dispute-resolution mechanism. The need for such ties increases as technical interdependency rises.

This is the mirroring hypothesis, with causal effects running from technical dependencies to organizational ties.

Conway (1968) focused on the process of designing a complex system. Before the design process can start, he noted, there must be a provisional partitioning of the system into subsystems and components. On the basis of that preliminary idea, task groups are formed and activities delegated to those groups. Within the task groups there will be many communication links, while across groups there will be few or none at all.

Conway argued that, for there to be a dependency between two components of the larger system, the designers of those components must have previously negotiated and agreed upon an interface specification, because technical components generally do not work together by pure chance. Thus, the presence of a working technical dependency is evidence of prior communication and cooperation, that is, organizational ties, between the designers. Conversely, if there is no communication and cooperation between designers, there can be no effective dependencies between their components (although there may be latent dependencies that cause the system to break down).

In other words, the existence of organizational ties can affect the placement of technical dependencies and thus influence the technical architecture of the system under development. This conjecture became known as Conway's Law: "organizations which design systems . . . are constrained to produce designs which are copies of [their] communication structures." (*ibid*. p. 31).

This is also the mirroring hypothesis, but with causal effects running from organizational ties to technical dependencies.

There is a tendency among management scholars to view technical dependencies as facts of nature and organizational ties as targets of design. There is a symmetric tendency among engineers and product developers to view the technical system as malleable while organizational ties are fixed by precedent, routines, and decisions made higher up the chain. In fact, both technical dependencies and organizational ties can be changed albeit at some cost. Furthermore, a competitive market economy will reward those combinations of technical architecture and organizational structure that deliver the greatest value at the least cost.

2.4 Mirroring across firms

The mirroring hypothesis entered the strategy literature via seminal works by Langlois and Robertson (1992) and Sanchez and Mahoney (1996). The key insight was that the absence of technical and organizational ties might determine or predict the location of firm boundaries. Thus, technical systems made up of many discrete modules can be implemented by loosely coupled organizations, i.e., separate firms, while systems with many interdependencies require tighter coupling such as is found in a single firm. Confirming this possibility, Baldwin and Clark (2000) described the vertical disintegration of the computer industry following the introduction of System/360, the first modular computer system. They observed that the arrival of a new modular product architecture provides opportunities for entry by specialized module makers.

Langlois (2002) then made the case that firms are non-modular structures with ambiguous internal boundaries that facilitate "communication of rich information" (p. 34). Baldwin (2008) went on to argue that transaction costs are low at module boundaries and high in module interiors; thus, by the logic of transaction cost economics (Williamson, 1985), the boundaries of firms should correspond to the boundaries of the underlying technical modules. These arguments were placed in a dynamic context by Wolter and Veloso (2008) who pointed out that obsolescence risk and the need to preserve outside options create forces causing fragmentation, and therefore firms and industries experiencing modular or radical innovations may have a propensity to break apart. Thus, from a dynamic perspective, "modularization as a process" (cf. MacDuffie, 2013) may underlie changes in industry and organizational structure, a possibility we explore in Section 5 below.

An important caveat to the mirroring hypothesis arises with regard to technical knowledge. Recall that information hiding is a key justification for the creation of modules. People working in one part of a modular system can focus on tasks related to their module and do not need to know what is happening in other modules. This partitioning of knowledge reduces the amount of knowledge needed by any one person or group, and thus is a valuable attribute in any system that depends on boundedly rational individuals. Following the logic of information hiding, a simple version of the mirroring hypothesis would predict that knowledge, like tasks, would be divided up in accordance with the modular structure of the underlying technical system.

This simple view has been challenged by a stream of work on system integration initiated by Brusoni *et al.* (2001) and Brusoni and Prencipe (2001). Observing the design and construction of complex technical systems involving many firms, they found that whereas the systems were modular (and mirrored) with respect to technical dependencies and most tasks, the *systems integrator* had to interactively coordinate and manage the entire network of component suppliers. To fulfil this coordination role, systems integrators needed capabilities that spanned a wide range of technical fields. As a result, their knowledge extended well beyond what was directly relevant to the tasks they performed in-house. Thus, a simple version of the mirroring hypothesis, based on strict information hiding, must be qualified in the case of the knowledge of systems integrators. Such firms "know more than they make" (Brusoni *et al.*, 2001: 597).

Indeed this observation applies to any firm that seeks competitive advantage through strategic manipulation of its boundaries and surrounding "industry architecture" (Jacobides, 2006). Managers can influence what an organization learns, and thus affect a firm's future capabilities and ability to adapt (Teece *et al.*, 1997; Jacobides and Winter, 2012). Overly strict mirroring of knowledge with task dependencies is likely to prevent a firm from seeing opportunities to change its boundaries and/or restructure its industry. Thus, while mirroring conserves scarce cognitive resources, hence is efficient in the short run, strict mirroring can be a trap. Instead, in technologically dynamic industries, firms must scan both new technologies and current contracting arrangements to identify "bottlenecks" that may be controlled by changing technical dependencies and organizational ties to create new institutional arrangements (Jacobides *et al.*, 2006; Pisano and Teece, 2007; Baldwin, 2015).

Viewed over time, technical and organizational architectures can be seen as dynamically changing and a source of strategic opportunity. However, such changes do not take place in a vacuum. MacDuffie (2013) has argued that modularity is not a simple property that can be changed via managerial fiat, but instead is the result of a learning process that involves "mapping functions to components ... and then setting out to learn and master the remaining interdependencies ... to make sure that interfaces can accommodate them" (p. 11). Baldwin and Clark (2000) describe this micro-process as one involving knowledge accumulation followed by purposeful information hiding. Designers must first map technical dependencies and determine their causes, then selectively eliminate interdependencies through the creation of design rules governing architecture, interfaces, and tests. "Modularization as a process" is lengthy and arduous, but it cannot be set aside. Premature modularization misses latent interdependencies, which detract from performance and may cause the system to fail entirely.

2.5 Descriptive and normative versions of the hypothesis

The mirroring hypothesis contends that there exists a correspondence (homomorphism) between the network of technical dependencies between tasks and the network of organizational ties between the people performing the tasks. From a research perspective, the hypothesis can be approached as either a descriptive prediction or a normative recommendation. From a descriptive standpoint, the hypothesis *predicts* a correlation between technical dependencies and organizational ties. From a normative standpoint, the hypothesis can be taken as a *recommendation* regarding the best way to set up a technical system and corresponding organization. In the next sections, we explain how these different points of view lead to different empirically testable hypotheses.

2.6 Mirroring as a descriptive hypothesis

Empirical researchers who approach the mirroring hypothesis in a descriptive fashion generally do not presume that any agent had the strategic intent to create a mirrored or unmirrored system. Often they are agnostic as to whether mirroring is likely to enhance or detract from an organization's performance. These researchers seek instead to establish the presence or absence of mirroring as a descriptive fact, by looking at correlations between technical dependencies and organizational ties in cross-section or over time. Implicitly or explicitly, they test the following hypothesis:

H1: In a complex technical system, organizational ties are more likely to exist in places where technical interdependencies are present (or dense). Organizational ties are likely to be absent where technical interdependencies are absent (or sparse).

To test the descriptive form of the mirroring hypothesis, researchers must collect data on the dependencies between technical components and separately collect data on task assignments, organizational ties, and firm boundaries. They can then look to see whether organizational ties are correlated with the presence of technical dependencies. High correlation is evidence in favor of the descriptive hypothesis: low or no correlation is evidence against it.

Within and across firms, the three main types of organizational ties themselves tend to be correlated. Communication is easier within teams and within firms than across teams or firms (King, 1999; Kleinbaum *et al.*, 2008). Employees of the same firm are often geographically collocated, and collocation itself makes communication easier. Thus, the presence of one organizational tie may be a proxy for others within and across firms.

2.7 Mirroring as a normative hypothesis

Complex technical systems and organizations are man-made systems. Their structures can arise through an evolutionary process as described above, but they are also targets of design (Baldwin and Clark, 2000; Jacobides, 2006; Puranam *et al.*, 2014). The designers of technical systems are boundedly rational—they cannot know or do everything. Thus, organizations are needed to carry out complex design and production processes. For system architects and organization designers, the design challenge is to create *a technical architecture and corresponding organization* that together are capable of carrying out complex tasks and solving problems that may come up along the way.

A mirrored system, we have seen, is an economical way to set up a complex technical system. It places problem-solving resources where problems are most likely to appear. Thus, architects and managers may consciously want to create mirrored organizations. And, if their conjectures are correct, mirrored organizations will perform well, and unmirrored organizations will perform poorly.

However, mirroring is only one design option. In some cases, a strictly mirrored system may preclude firms from anticipating or pursuing architectural innovations. In other cases, it may be prohibitively costly or logistically infeasible. Thus, architects and managers may trade-off the economy of strict mirroring in favor of other benefits or in response to organizational limitations and constraints. They may consciously seek to create partially mirrored systems or even unmirrored systems.

Empirical researchers approaching the mirroring hypothesis from a normative perspective assume that some designer or team intended to create a mirrored or unmirrored system. They then correlate the system design—mirrored, partially mirrored, or unmirrored—with one or more measures of system performance. Implicitly or explicitly, they test the following hypothesis:

H2: Mirrored systems achieve good performance outcomes, and unmirrored systems achieve poor performance outcomes.

To test this version of the hypothesis, researchers must first collect data on the extent of mirroring in a given system and then evaluate the performance of the organization. High rates of success for mirrored systems and/or low rates of success for unmirrored systems are evidence for the hypothesis; the converse patterns are evidence against the hypothesis.

We now move on to review the empirical evidence on mirroring from both a descriptive and normative perspective.

3. Empirical evidence on the mirroring hypothesis: data and methods

In this and the following sections, we report the results of a survey and synthesis of the empirical evidence pertaining to the mirroring hypothesis. We first describe how we obtained and analyzed our sample. We then present an overview of the results. Detailed findings are given in Supplementary Appendix A. A tabular description of the data is presented in Supplementary Appendix B. Works in the sample are listed separately in the References section of this article.

We were able to identify 142 separate studies, in a wide range of settings, in which both technical dependencies and organizational ties were observed and their correspondence assessed in a rigorous quantitative or qualitative fashion. The studies were divided into two groups: an extensive compilation of 103 studies published before and during 2009 and a supplementary compilation of 39 studies published since then. We used the supplementary group as a means of checking on the validity of our framework and identifying new trends.

In our sample of 142 studies, just under half (68) took a descriptive stance, looking at correlations between technical dependencies and organizational ties either in cross-section or over time. Slightly over half (74) took a normative stance and evaluated the success and/or failure of mirrored and unmirrored systems. Each study constitutes an observation of a case in which the descriptive or normative version of the mirroring hypothesis might or might not hold. We believe it is worthwhile to examine this evidence critically, summarize it statistically, and identify commonalities and differences among the separate studies.

3.1 Sample selection

We began in 2009 by conducting an electronic search for relevant scholarly works across the full digital publication lives of 19 major journals spanning multiple disciplines. These journals are listed in Table 1. To cast a wider net for the nascent literature on open collaborative projects, we repeated the search using the Association of Computer Machinery (ACM) Portal's Guide to Computing Literature. We used a broad set of keywords to perform the search: these appear in Table 2.

We examined titles and descriptions of the search results to remove duplicates, bibliographies, editors' commentaries, book reviews, pure theory works, directions for future research, experiments and simulations, technical "white papers" and unrelated articles. We then examined the abstracts of the 141 remaining candidates and removed another 35 due to lack of direct relevance (e.g., the article investigated technical architecture or organizational structure but not both). After this initial filtering, we expanded the sample in two ways. First, in a snowball type search, we scanned the retained articles for relevant studies that were not yet included. We also added studies with which we were familiar. We reviewed the full contents of the 130 studies in the resulting set. We found that 27 did not have sufficient data to correlate technical dependencies with organizational ties, and dropped these from the sample.

In 2015, we undertook a second snowball search aimed at capturing salient works published since 2009. We identified 59 potentially relevant studies, applied the same screens as in the initial sample, and obtained 39 studies that met our criteria for inclusion. We first analyzed the two groups separately and then checked to see if the results were similar. On the whole, we found the results to be consistent, and thus we felt comfortable pooling the two samples.

The resulting sample included 146 articles and books, but only 142 separately classified studies, since some works contained more than one study and others contained duplicate discussions of the same study. Of these, 140 were reported in scholarly works; two were reported in books describing the personal experiences of the chief architect of a development project (Mead and Conway, 1980; Colwell, 2005). We believe the two studies based on personal experience constitute valid empirical observations, but our results would not be significantly affected by their exclusion. Although large, the sample is not exhaustive: some relevant studies undoubtedly escaped our net. Nevertheless, the sample is broad-based and (we believe) representative of scholarly empirical work through the middle of 2015.

Table 1. Journals included in the initial search for empirical evidence

Academy of Management Journal	Journal of Management Studies
Academy of Management Review	Journal of Product Innovation Management
Administrative Science Quarterly	Management Science
California Management Review	Managerial and Decision Economics
Harvard Business Review	Organization Science
IEEE Engineering Management Review	Organization Studies
IEEE Software	Research in Engineering Design
IEEE Transactions on Engineering Management	Research Policy
Industrial and Corporate Change	Strategic Management Journal
Industry and Innovation	

Table 2. The keyword string used in the initial search for empirical evidence

((modular OR modularity OR “product architecture”) AND “division of labor”) OR
((modular OR modularity OR “product architecture”) AND “organizational structure”) OR
((modular OR modularity OR “product architecture”) AND “industry structure”) OR
((modular OR modularity) AND “open source”) OR “task partitioning”

Table 3. Breakdown of studies in the core sample by industry and year of publication

All studies	Before 2000	2000–2001	2002–2003	2004–2005	2006–2007	2008–2009	2010–2011	2012–2013	2014–2015	Total
Information-based industries										
Software	3	2	5	6	8	6	2	4	3	39
Digital media						1				1
Semiconductors	4		2		5	1		2	1	15
Computers	2	3	1		1	2	1		2	12
Telecommunication			2							2
IT support				1			1			2
Diverse IT				1						1
Total	9	5	10	8	14	10	4	6	6	72
Manufacturing industries										
Autos	2	3	1	2	4	1		5	1	19
Aircraft and defense	2	2		1	1	2	1	1	1	11
Chemical				1	1					2
Steel					1					1
Metals						1				1
Manufacturing equipment	1			1				1		3
Air conditioning									1	1
Sci instruments						1			1	2
Home appliances			1							1
Power tools	1									1
Cameras						1				1
Sports and games		1			2	1	1			5
Stereos	2									2
Clothing					1					1
Food									1	1
Pharmaceuticals								1		1
Diverse Manufacturing	2			1	1	1		3	2	10
Total	10	6	2	6	11	8	2	11	7	63
Other industries										
Banking				1		1				2
Construction	1			1			2		1	5
Healthcare								1		1
Professional services									1	1
Total	1	0	0	2	0	1	2	1	2	9
Grand total	20	11	12	16	25	19	8	18	15	144

Table 3 shows the distribution of studies by industry and publication year. Two studies (Langlois and Robertson, 1992; Collinson and Wilson, 2006) covered two industries, hence are counted twice in the table. The studies are widely distributed across industries and over time, but this is far from a random sample. Software is most heavily represented with 39 studies. Almost half of the software studies (19) describe open-source projects: interest in this new organizational form grew between 2002 and 2009 and then dropped off, accounting for the rising and falling trend.

Autos (19) and semiconductors (15) have the next highest number of studies followed by computers (12) and aircraft and defense (11). Information-based industries are overrepresented, while continuous process, extractive, and service industries are underrepresented in the sample.

3.2 Analysis

For the 103 studies in the initial sample, we examined and coded the studies' research designs and results to facilitate cross-comparisons. In particular, we noted whether the methodology employed was primarily quantitative (e.g., statistical correlation of design dependencies with organizational variables such as outsourcing/insourcing) or qualitative (e.g., interviews or surveys of perceived correlations between design dependencies and organizational variables). In this preliminary analysis, we divided our sample into subgroups according to the type of organization, but did not distinguish between descriptive and normative studies. We reported the results of our preliminary analysis in a 2010 working paper, and described some of the common features of the exceptions that contradicted the mirroring hypothesis. We then put the study aside until 2015.

In 2015, on the encouragement of reviewers, we updated the sample and separated studies that were mainly descriptive from those that took a normative perspective. We also divided the studies of firms into (i) within-firm studies; (ii) studies of buyer-supplier relations; (iii) studies that looked at the management of knowledge; and (iv) studies of strategic alliances and consortia. By looking at these subgroups, we were able to classify the results in a more nuanced and theoretically consistent way.

4. Overview of findings

This section presents an overview of our findings.

4.1 Descriptive studies

As indicated, the descriptive studies in the sample, numbering 68, sought to establish correlations between technical and organizational variables. In the industry studies, the correlation studied was between a one-time change in product or process architecture and a corresponding change in industry structure. In the rest of the studies, the correlation studied was between measures of technical interdependency and measures of organizational linkages such as communication between developers or insourcing of components. Accordingly we classified the descriptive studies as exhibiting (i) high, (ii) partial, or (iii) no correlation between technical interdependency and organizational ties. Results for all groups involving firms are reported in Table 4. Results for open collaborative projects are reported in the first panel of Table 6.

4.2 Normative studies

The normative studies, numbering 74, sought to evaluate the performance outcomes associated with different ways of organizing work. The question in these studies was not, is mirroring prevalent, but instead, what are the performance consequences of setting up an organization to be mirrored or not. A study can support the normative form of the mirroring hypothesis by showing that the performance of mirrored organizations is good or the performance of unmirrored organizations is poor. Symmetrically, a study can fail to support the hypothesis by finding unmirrored organizations that performed well or mirrored organizations that performed poorly. Thus we adopted a six-part classification scheme for normative studies: (i) mirrored performed well, (ii) mirrored performed poorly, (iii) partially mirrored performed well, (iv) partially mirrored performed poorly, (v) unmirrored performed well, and (vi) unmirrored performed poorly.

Table 5 reports the results for the normative studies involving firms. The second panel of Table 6 reports the results for open collaborative projects.

4.3 Summary of findings

The descriptive studies of industries and firms showed that correlation between technical interdependencies and organizational ties is a common pattern both cross-sectionally and over time. Over two-thirds (70%) of these studies provide strong evidence of mirroring; 22% provide partial support; while only 8% do not support the hypothesis.

Table 4. Results for descriptive studies of firms

Finding	#	%	Categorization
Industry studies			
Mirrored	7	100	Dynamic mirroring
Within firm			
Mirrored	12	75	Technical dependencies correlated with communication linkages
Partially mirrored	3	19	System integration correlated w/cross-module communication
Unmirrored	1	6	Technical interdependence uncorrelated w/communication (software = 1)
Total	16	100	
Buyer-supplier relations			
Mirrored	13	76	Modularity of components correlated w/outsourcing
Partially mirrored	1	6	Novel components exhibit high levels of communication between buyer and supplier
Unmirrored	3	18	Technical interdependence uncorrelated w/communication (software = 2)
Total	17	100	
Management of knowledge			
Mirrored	2	33	Patent citations mirror organization ties (1); Patent portfolios mirror product architecture (1)
Partially mirrored	4	67	Concurrent sourcing (2); Patent portfolios do not mirror product architecture (1); Ownership not correlated w/physical flows (1)
Total	6	100	
Alliances and consortia			
Mirrored	1	25	Modularity correlated w/loosely coupled organizations
Partially mirrored	3	75	Interdependence weakly correlated w/communication (2); Modularity weakly correlated w/loosely coupled organizations (1)
Total	4	100	
All groups involving firms			
Mirrored	35	70	Dynamic mirroring (7); Dependencies correlated w/communication (12); Modularity correlated w/outsourcing (13); Other (3)
Partially mirrored	11	22	System integration correlated w/cross-module communication (3); Various weak correlations (8)
Unmirrored	4	8	Technical interdependence uncorrelated w/communication (4, of which 3 are in software)
Total	50	100	

Support for the descriptive hypothesis is strongest in the industry studies, which generally showed that dynamic changes in technical architectures were followed by corresponding changes in industry structure. Support is also strong in the within-firm studies and in studies of buyer–supplier relations. Notably, however, in the latter two groups, about 25% of the studies showed partial or no mirroring, indicating that while mirroring is a common pattern, it is not universal.

Support for the descriptive hypothesis is markedly lower in studies of the management of knowledge and alliances and consortia. In these sub-groups, partial mirroring, in which firms explicitly invest in knowledge of technologies beyond their task boundaries, is the most commonly observed pattern.

The normative studies of firms offer a more nuanced view of mirroring as an organizational choice. Supporting the hypothesis, in 21 cases (of 64), mirroring was an explicit organizational goal and such organizations generally performed well. Further supporting the hypothesis, in 10 cases, unmirrored organizations performed poorly. The common thread linking the poor performers was *premature modularization*. These firms attempted to create modular organizations in response to new, supposedly modular technical architectures. However, they lacked knowledge of latent technical interdependencies; hence, their organizational ties turned out to be unmirrored with respect to the

Table 5. Results for normative studies of firms

Finding	#w	%	Categorization
Industry studies			
Mirrored performed well	2	67	Dynamic mirroring strategy
Mirrored performed poorly	1	33	Mirroring 'trap'
Total	3	100	
Within firm			
Mirrored performed well	8	44	Mirroring is an explicit design goal of system architect (4); Mirrored systems perform well (4)
Unmirrored performed poorly	4	22	Premature modularization
Partially mirrored performed well	2	11	System integration requires cross-module coordination
Unmirrored performed well	4	22	Dynamic contra-mirroring strategy
Mirrored performed poorly	2	11	Mirroring 'trap'
Total	18	100	
Buyer-supplier relations			
Mirrored performed well	11	34	Mirrored systems perform well (5); Dynamic mirroring (4); Other (2)
Unmirrored performed poorly	6	19	Premature modularization
Partially mirrored performed well	12	38	System integration requires cross-module coordination (7); Relational contracts perform well (2); Other (3)
Unmirrored performed well	3	9	Relational contracts perform well
Mirrored performed poorly	3	9	Mirroring 'trap' (2); Other (1)
Total	32	100	
Management of knowledge			
Partially mirrored performed well	4	100	Firms w/broader knowledge perform well
Total			
Alliances and consortia			
Partially mirrored performed well	2	25	Relational contracts perform well
Unmirrored performed well	6	75	Relational contracts perform well
Total	8	100	
All groups involving firms			
Mirrored performed well	21	33	Mirrored systems perform well (9); Dynamic pro-mirroring strategy (6); Mirroring explicit design goal (4); Other (2)
Unmirrored performed poorly	10	16	Premature modularization
Partially mirrored performed well	20	31	System integration (9); Firms w/broader knowledge perform well (4); Relational contracts perform well (4); Other (3)
Unmirrored performed well	13	20	Dynamic contra-mirroring strategy (4); Relational contracts perform well (9)
Mirrored performed poorly	6	9	Mirroring 'trap' (5); Other (1)
Total	64	100	

true underlying technical architecture. The firms dealt with these unexpected interdependencies in an *ad hoc* fashion, and their performance suffered as a result.

Partial mirroring, in which knowledge boundaries are drawn more broadly than operational boundaries, was observed in 20 of the normative studies. Notably, all firms that adopted this strategy performed well; hence, the finding "partially mirrored performed poorly" does not appear in Table 5. We believe this asymmetry is caused by the selection of research sites. Management scholars often seek to identify best practices (e.g., in systems integration) and thus select successful firms for study. Our sample indicates that many successful firms practice partial mirroring, but it does not tell us whether other firms have adopted this strategy and failed.

The normative studies also showed that it is possible for firms to strategically 'break the mirror' and perform well. One possibility is to implement modular partitions within their own boundaries. A second possibility is to build relational contracts that support high levels of technical interdependency across firm boundaries. Both types of

Table 6. Results for open collaborative projects

Finding	#	%	Categorization
Descriptive Studies			
Mirrored	5	28	Open-source codebases are modular w/low cognitive complexity (4); Technical interdependence correlated w/communication (1)
Partially mirrored	3	17	Core-periphery organization structure (2); Most tasks performed by one person, but two-person groups do not communicate (1)
Unmirrored	10	56	Transient groups work interdependently in brief spurts (5); Core developers contribute to many modules (4); Flawed study (1)
Total	18	100	
Normative studies			
Mirrored performed well	3	75	Small teams with narrow responsibilities perform well (2); Other (1)
Unmirrored performed poorly	1	25	Interdependent component w/multiple authors performs poorly
Total	4	100	

strategic mirror-breaking can be a source of competitive advantage. We discuss within-firm modularizations in Section 5 and relational contracts in Section 6 below.

Last but not least, there is evidence of a mirroring 'trap' in the normative studies. In five cases, firms focused on the current technical architecture fell victim to architectural innovations originating outside their boundaries.

The evidence from open collaborative projects paints a very different picture from the studies involving firms. Here the majority of descriptive studies (56%) *did not* support the mirroring hypothesis. The normative studies were generally supportive of mirroring but too few in number to be decisive. Below in Section 7, we will argue that these contradictory results arise because digital technologies make possible new modes of coordination that enable groups to deviate from classical mirroring as seen within firms.

The next three sections consider themes that cut across all analytical categories. Our intent is to bring together evidence from across the sample to reveal larger patterns. The themes we consider are as follows: (i) the dynamics of mirroring, (ii) collaboration across firm boundaries, and (iii) the new economics of digital tools and technologies.

5. The dynamics of mirroring

While we initially cast the descriptive and normative forms of the mirroring hypothesis as static propositions, there is ample theory and evidence that mirroring is in fact a dynamic process. Our initial formulations tested for the prevalence and performance of technical and organizational systems that were (or were not) mirrored at a specific point in time. However, in many cases, the researchers observed systems that were in flux, responding to new technological possibilities, new managerial strategies, or both. Viewing such cases longitudinally gives us insight into how mirroring relationships evolve over time.

Consider first the industry studies. In 9 of 10 cases, the industry was originally mirrored and its firms well adapted to the existing technical architecture. Then a new architecture was discovered with a better value proposition. The incumbents' organizational structures were misaligned relative to the new technology, and thus their organizations could not effectively respond to it. In the ensuing competition, firms either adapted their organizational structure (became mirrored) or exited.

In all seven descriptive industry studies, the new technical architecture was *more modular* than the dominant architecture at the time, and the industry subsequently broke apart. Typically, once the more modular architecture was in place and standards widely disseminated, specialized firms entered the industry by offering modules that competed with and eventually replaced the products of vertically integrated firms (Baldwin and Clark, 2000; Consoli, 2005; Galvin and Morkel, 2001; Jacobides, 2005; Langlois and Robertson, 1992; Lecocq and Demil, 2006; Sturgeon, 2002).

In two of the normative industry studies, industries evolved in the other direction, toward consolidation. In the case of bicycle drive trains, Shimano introduced a superior integrated product, the demand for modular products evaporated, and specialist firms exited the industry (Fixson and Park, 2008). In the British construction industry, unresolved technical interdependencies in the building process led specialist firms to merge, leading to significant industry consolidation (Cacciatori and Jacobides, 2005).

In contrast, in the third and final normative industry study, Sheffer and Levitt (2010) and Sheffer (2011) describe how the currently fragmented US construction industry (which mirrors current technology and building practice) is unable to implement system-level innovations that require coordination across firm boundaries. In this case, a mirrored industry structure is performing poorly in that it cannot access new opportunities involving technical architectures that do not mirror the current industry structure.

The evidence from the US construction industry thus suggests the existence of a mirroring 'trap'. This warning is echoed in four other studies. Henderson and Clark (1990) found that well-mirrored incumbents making photolithographic equipment lacked the internal capabilities to assimilate—or even perceive the advantages of—architectural innovations. Similarly, in the chemical, steel, and pharmaceutical industries, Collinson and Wilson (2006) and Dougherty and Dunne (2012) found that communication patterns and problem-solving strategies that had evolved under a prior technical architecture, prevented companies from perceiving innovations that cut across organizational boundaries. The consequences can be severe: Brusoni and Prencipe (2011) showed that reliance on the organizational ties developed under a previous technical architecture led to the grounding of two aircraft fleets due to design flaws.

The mirroring 'trap' is precisely the trap identified in the exploration-exploitation literature as a failure to explore (March, 1991; Benner and Tushman, 2003; Tushman and O'Reilly, 2004). Firms can avoid this trap via partial mirroring, in which they define their knowledge boundaries more broadly than their task boundaries. Although this strategy runs counter to strict information hiding, our sample indicates that it is both common and highly effective, as evidenced by 16 studies of buyer–supplier relations and the management of knowledge. Systems integrators who are responsible for the performance and evolution of an entire technical system are especially likely to adopt partial mirroring.

Partial mirroring is effective because, in complex systems with changing technologies, tasks and decisions are often more interdependent than system designers realize. Until a system is well-understood, latent dependencies will be present that can greatly compromise system performance and may cause a new system to fail. The 10 studies in our sample of poor performance due to premature modularization attest to this possibility. Partial mirroring strategies, by viewing the current technical architecture in a broader context, may identify these latent dependencies, and thus appropriately mirror the interdependencies that will affect the *next* generation of the product or process.

Significant architectural innovations are sometimes initiated by single firms in pursuit of competitive advantage. We have already discussed Shimano's introduction of an integrated bicycle drive train and its subsequent impact on the structure of that industry: in that case, Shimano's technology mirrored its own organization, but not that of its industry. In four other cases, tight-knit teams within single firms successfully created and capitalized on *modular* product architectures that did not mirror their own organizations (at least initially).

To understand the significance of these four cases, it is important to note that modular technical architectures do not arise naturally within firms. Communication linkages, collocation, and willingness to cooperate all work against the strict rules and information hiding that define truly modular systems. Thus, it is very common within firms for theoretical modules to collapse into one, large interconnected system.

Nevertheless, through an intense collaborative effort across multiple functional units, Black and Decker created an internal, modular product platform that allowed it to produce a wide range of power tools with standard components (Lehnerd, 1987). Sony designed the Walkman in the same way: as a reconfigurable platform that supported high variety and low cost (Sanderson and Uzumeri, 1995). Faced with the threat of holdup over a license, a team of software developers successfully modularized their platform to isolate the problematic code from the rest of the codebase (LaMantia *et al.*, 2008). And when open-source developers rejected Mozilla's code because it was too complex, a team at Netscape redesigned the codebase so that it had the same functionality, but a higher degree of modularity (MacCormack *et al.*, 2006).

In each of these cases, engineers and managers at the firms in question perceived the advantages of a modular architecture and made it a top priority for the team developing the design. They worked against their own organizational tendencies, and sought to change the existing technical architecture, thus contradicting Conway's prediction that "organizations ... are constrained to produce designs which are copies of the communication structures of these organizations."

However, not all such endeavors are successful. When firms attempt to create modular product and process architectures, nature sometimes stops the process by exposing unknown but critical interdependencies. The auto industry provides an example. During the 1990s and early 2000s, several automakers, including Ford, sought to move the design and testing of modules to their suppliers to gain the benefits of lower labor costs and more rapid innovation cycles (MacDuffie, 2013; Jacobides *et al.*, 2015). However, as MacDuffie (2013) explains, "modularity as a property" cannot be instituted by corporate fiat: it relies on "modularization as a process" which involves identifying, researching, and resolving numerous technical interdependencies inherent in the technical structure of the vehicle. MacDuffie contrasts the modularization process at Ford, which was rapid but failed, with the process at Hyundai, which proceeded more slowly and appears to be succeeding. The dangers of premature or too-rapid modularization are borne out in nine other studies, four within firms and six involving buyers and suppliers.

High levels of complexity and high rates of technical change are characteristic of the most influential and dynamic sectors of modern economies. Our evidence on the dynamics of mirroring shows that, when systems are complex and technologies are changing rapidly, system knowledge is necessarily incomplete. Given incomplete knowledge, those guiding the evolution of these systems will not be able to perceive and account for all true underlying technical interdependencies in their explicit interface definitions. Understanding of the whole remains imperfect and incomplete even after much effort and many iterations. *In such cases, organizational processes that deviate from strict mirroring are likely to be beneficial in terms of technical performance, competitive advantage, and the accumulation of valuable knowledge and capabilities.* A "partial mirroring" strategy can be an effective way to explore and understand latent interdependencies that are not apparent under the current technical architecture. Furthermore, if the stakes are sufficiently high, firms may go further, overturning the current architecture for their own strategic advantage. Strategic mirror-breaking, if successful, can bring about wholesale changes to industry structure.

6. Collaboration across firm boundaries

The mirroring of technical dependencies with the boundaries of firms is the most common pattern in our sample of studies involving firms. However, there is also evidence that firms can sometimes manage dense technical interdependencies across their boundaries. A number of studies of buyer–supplier relations document early supplier involvement in the design of components, ongoing technical communication, and generally cooperative behavior on both sides of the relationship (Andersen, 1999; Bonaccorsi and Lipparini, 1994; Dibiaggio, 2007; Howard and Squire, 2007; Langner and Seidel, 2009; Miozzo and Grimshaw 2005; Sako, 2004). Supplier involvement and information sharing may vary across components in the same system: more complex and/or novel components generally are associated with higher levels of communication between buyers and suppliers (Monteverde and Teece, 1982; Novak and Eppinger, 2001; Takeishi, 2001, 2002; Cantamessa *et al.*, 2006; Cabigiosu and Camuffo, 2012: Furlan *et al.*, 2014). Another group of studies describes the workings of alliances and consortia, where multiple firms participate in the development of a tightly integrated, technically challenging new product or system (Appleyard *et al.*, 2008; Argyres, 1999; Barlow, 2000; Miller *et al.*, 1995; Scott, 2000; Snow *et al.*, 2011; Staudenmayer *et al.*, 2005; Tuertscher *et al.*, 2014).

Much of the theory relevant to these exceptional cases has been developed since 2010. First is the idea of "epistemic interdependence" discussed in Section 2 (Puranam *et al.*, 2012); second is the concept of "relational contracts" from economics and sociology; third is the idea of reciprocal learning leading to shared understanding. These concepts help to explain why and how independent firms can 'break the mirror' and work collaboratively on highly interdependent technical problems or systems.

Epistemic interdependence gives rise to the need for real-time coordination, which is facilitated by organizational ties (Puranam *et al.*, 2012). Epistemic interdependence in turn is closely related to novelty. If a technical interdependence is well understood, it can be addressed via a rule or standard (Baldwin and Clark, 2000). But this process requires knowledge, and for this reason, novel technical systems and innovative components within existing systems will generate epistemic interdependence and thus call for higher-than-normal levels of communication and cooperation between the actors involved (Furlan *et al.*, 2014).

Opportunities to create novel technical systems and/or innovative components often arise at the boundaries of firms. Indeed, all the cases of alliances and consortia in our sample involved the creation of new, technically challenging products or systems. Similarly, the cases involving higher-than-normal levels of buyer–supplier communication and cooperation generally involved novel or one-of-a-kind components. In other words, these firms were engaged in what Parmigiani and Rivera-Santos (2011) call "co-exploration" to develop new knowledge rather than "co-exploitation" of existing knowledge. Co-exploration involves "joint decision-making and rich ongoing communication between partners" which implicitly requires firms to 'break the mirror' by dissolving their organizational boundaries for the task at hand.

In such cases, why not unite the actors within the boundaries of a single firm? In fact, Garud and Munir (2008) document one such case. When designing the film and batteries for the novel SX-70 camera, Polaroid attempted to work with its suppliers, but they were unresponsive and eventually the company elected to design and produce these components in-house. However, in the cases of successful across-firm collaboration in our sample, the knowledge and capabilities needed to pursue the opportunity were distributed across several firms, and assembling them under one roof would have been costly and time-consuming. Thus, the firms chose not to integrate, but instead to build *relational contracts*.

There are two definitions of relational contract in the literature, one derived from economics, the other from law and sociology. The economic form, as discussed by Baker, Gibbons, and Murphy (2002) and Gibbons and Henderson (2012), assumes that agents are self-interested but able to calculate the present value of a continuing relationship. The "shadow of the future" thus restrains short-run opportunistic behavior. In contrast, the legal and sociological concept of a relational contract assumes that agents are social beings subject to "entangling strings of friendship, reputation, interdependence, morality and altruistic desires" (Macneil, 1987: 276). Though theoretically distinct, these concepts overlap in practice. They also require parties to the relationship to solve two basic problems: the problem of credibility (persuading counterparties one will act in good faith) and the problem of clarity (reaching a consistent, shared understanding of what is expected) (Gibbons and Henderson, 2012).

The problem of credibility can be addressed in three ways. First, the participants must have compatible motivations, that is, a superordinate goal that all know—and know the others know—can only be attained through joint, cooperative effort. Credibility can also be enhanced through repeated interaction. Each time one party fulfills a promise or goes beyond minimal performance, the others take note and adjust their assessments of reliability upward. Finally, the parties can make relationship-specific investments, creating resources that have little or no value except in the context of a continuing relationship.

All cases of successful across-firm collaboration in our sample were characterized by compatible motivation. In the alliances and consortia, the motivation generally took the form of a new, advanced technology or product, such as a next-generation manufacturing process, a military aircraft, or an advanced scientific instrument that would benefit all participants, but which none could build alone (Appleyard *et al.*, 2008; Argyres 1999; Tuertscher *et al.*, 2014). In buyer–supplier relations, the motivation was generally a better performing component and/or a more harmonious, responsive relationship (Bonaccorsi and Lipparini, 1994; Sako, 2004). Notably some suppliers proactively sought high levels of involvement as a means of strategic differentiation (Andersen, 1999; Miozzo and Grimshaw, 2005).

Consistent with the predictions of both economics and sociology, the across-firm collaborations in our sample were also generally long-lasting and involved both repeated interactions and relationship-specific investments. For example, the Japanese automakers Toyota, Honda, and Nissan induced their suppliers to share knowledge by investing in their suppliers' capabilities: they created teaching programs to replicate their in-house capabilities at suppliers' facilities, and they set clear rules for sharing the resulting financial gains cooperatively (Sako, 2004). In another case, Apple and SCI entered a contract committing the two firms to jointly assess the feasibility of each other's innovations. The contract's enforceable portion consisted of a 3-year commitment by Apple to purchase parts manufactured by SCI. However, the contract also contained unenforceable sections, which, the authors argue, were designed to build the firms' knowledge of each other's capacity for good faith collaboration and dispute resolution (Gilson, Sabel and Scott, 2009: 466).

The problem of clarity identified by Gibbons and Henderson (2012) is in fact part of a larger problem: how can diverse parties with few organizational ties work together effectively on a complex, technically interdependent product or system? To coordinate their actions in the face of underlying epistemic interdependency, *participants must develop a shared understanding* of the underlying technical system. In other words, contributors need to be able to "speak the same language" in terms of how they explain and interpret technical data and decisions. They also need to be able to anticipate when, where, and how to look for information from their counterparts.

In some cases in our sample, contributors lacked a shared understanding at the outset of the relationship, but subsequently invested time and effort to develop one. For example, Chrysler initially outsourced the development of windshield wipers for the Jeep Cherokee using a modular design approach with explicit interface specifications (Mikkola, 2003). Unfortunately, the supplier did not understand some of the specifications, the design failed, and the firms had to start over "from scratch" (p. 449). In the second (successful) design effort, Chrysler and the supplier increased the flow of technical information across their boundary: "Face-to-face meetings…daily phone calls, etc.

became a habit" (p. 450). Sharing technical information in this way allowed the engineers at both firms to develop and maintain a common, accurate understanding of the evolving product design.

Across all cases of successful across-firm collaboration, we found that the mechanisms used by collaborating groups to share design information fell in two classes: (i) those that were analogues of traditional organizational ties; and (ii) those that constituted a genuine departure from tradition. The analogues to traditional organizational ties included broadband electronic (instead of face-to-face) communication, temporary physical collocation, and status-based planning and dispute resolution. These devices created a set of direct, though informal, organizational ties between participants. In other cases, however, independent contributors did not develop as many direct ties, but coordinated their efforts implicitly, via shared product design and development tools. In these cases, transparency and direct involvement with the design served as a partial or complete substitute for direct ties between designers.

7. The new economics of digital tools and technologies

Digital technology has radically reduced both design and communication costs, which lie at the core of the economics of mirroring. In the 1990s, the ever-decreasing cost of computers and advent of the Internet gave rise to a variety of new organizational forms that were not firms. Among the most important was a new form of development organization based on open collaborative work, self-selection of tasks, and free sharing of intermediate and final designs (Boudreau and Lakhani, 2015). This community-based model of development is most evident in the arena of open-source software (Raymond, 2001), but it arises in sports and other communities as well (Franke and Shah, 2003; Baldwin *et al.*, 2006). Quite often the development effort is spurred by users or people close to users (e.g., the parents of sick children) who have a strong interest in advancing a technology that for-profit firms are not pursuing.

Significantly, of the three organizational groups in our sample, open collaborative projects, most of which focused on software, provided the least support for the mirroring hypothesis.[6] In this section, we look more closely at studies of open collaborative projects to see what effect digital technologies have had on mirroring. Three patterns are noteworthy: (i) the use of digital technology to assemble transient groups of problem-solvers to work interdependently for limited periods of time; (ii) technical systems with high modularity and low cognitive complexity but no information hiding; and (iii) core-periphery technical and organizational structures, which might or might not be mirrored. We discuss each of these patterns below.

First, digital technologies make it possible to assemble groups of problem solvers to work intensively on relatively small problems for limited spans of time. If the participants work independently, disclosing only their final solutions, then their technical dependencies and organizational ties will be mirrored. But in open collaborative projects it is more common for participants to see and build on each other's work. Thus in the GNU Project of the Free Software Foundation, Elliott and Scacchi (2003) found that geographically distributed contributors collaborated directly—often in real time—using mailing lists and instant messaging. Similarly, in the FreeBSD project, Spinellis (2006) found that developers from different parts of the world contributed to the same module on the same day.

Indeed, contributors do not need to cooperate to work interdependently: in some software contests competitors can see each other's code, adopt it, and modify it with no explicit constraints[7] (Gulley, 2001, 2004; Lakhani *et al.*, 2013; Boudreau and Lakhani, 2015). Observing a number of such contests, Gulley (2004) found that contestants made rapid, iterative changes to each other's work so that the winning entry manifested the "tangled effort of dozens of people" (p. 23). These dynamics have also been observed in sports competitions and open innovation contests (Baldwin *et al.*, 2006; Kokshagina *et al.*, 2015).

For this mode of collaboration to be feasible, participants must have not only broadband, all-to-all communication, but also tools that support rapid generate-test cycles (Simon, 1981). The emerging artifact must be easily understood (transparent) and subject to manipulation (actionable) (Zuboff, 1988; West and O'Mahony, 2008). Many digital artifacts have the property of actionable transparency. Physical artifacts are harder to act upon, although simulation models and technologies like 3-D printing shorten generate-test cycles and make them actionable to a degree.

The members of the ad hoc groups that form in open-source projects or participate in contests are mirrored in the sense of having dense communication linkages while they are working. Also, although they are not members of the

6 In the within- and across-firm studies, most software organizations were mirrored, but three were not (Grunwald and Kieser, 2007; Herbsleb et al. 2005; Srikanth and Puranam, 2011).

7 In effect, these regimes provide contestants with no property rights in their designs.

same firm, they work within frameworks—open-source communities or sponsored contests—that keep opportunism within the bounds of community norms and fair play. Hence, this pattern *does not contradict the mirroring hypothesis* so much as show that with digital technology, *temporary organizational ties can quickly be created at low cost to support highly interdependent collaboration*.

The second pattern we observed was the conundrum of high modularity and low cognitive complexity without information hiding. To attract the efforts of part-time and volunteer contributors, open collaborative projects cannot be too complex. Information hiding is the traditional way to reduce cognitive complexity: the problem is broken down into parsimoniously linked sub-problems; technical interdependencies are partitioned in modules; and each module becomes the responsibility of an interactive team of individuals (Simon, 1962; Parnas, 1972, 1978; Baldwin and Clark, 2000).

In fact, four studies in our sample found that open-source projects had lower cognitive complexity and were more modular than proprietary projects (Herraiz *et al.*, 2006; MacCormack *et al.*, 2006, 2008; Baldwin *et al.*, 2014). However, three other studies found no evidence of strict partitioning within codebases nor any correspondence between identifiable organizational groups and specific modules (Bird *et al.*, 2008; Bowman and Holt, 1998; Gutwin *et al.*, 2004). These studies contradict the idea that modularity and low cognitive complexity must be achieved through rule-based partitions and information hiding (Parnas, 1972, 1978).

This conundrum can be partially explained by the phenomenon of "hidden structure" in software codebases. Looking at a large sample of codebases developed in both open-source communities and in firms, Baldwin *et al.* (2014) found that most did not contain many separate modules but instead had a "core-periphery" structure, with one central module, or "core." Open-source codebases were more modular in the sense of having consistently smaller cores than comparable proprietary codebases. A small core in turn means that changes in one part of the system will not propagate as readily to other parts, and thus contributes to low cognitive complexity. Thus it is possible to have high modularity (low propagation) and low cognitive complexity without strict information hiding.

When the individual components of a technical system can be comprehended easily and changed readily without propagating into the larger system, developers may not need to communicate directly with one another. Instead, the system itself summarizes its own state and interaction with the changing system suffices to coordinate the work of many independent agents. This method of coordination is known as "stigmergy": it is characteristic of social insects, neuronal networks, chess games, data repositories, and distributed computing (Heylighen, 2006; Bolici *et al.*, 2009).

Stigmergic coordination is possible only if each task is epistemically independent of other tasks so that each actor can choose his or her best course of action without exchanging information with other actors. The studies in our sample provide evidence of stigmergic coordination especially with respect to small contributions: people inspect the state of the system, change it, submit their changes, and see what happens. Sophisticated tools make it possible to "track back" to previous system states if the changes turn out to be damaging.

However, even highly modular systems have some parts that are more complex and technically interdependent than others. Thus a third pattern we observed was the formation of a "core-periphery" organizational structure (Koch and Schneider, 2002; von Krogh *et al.*, 2003; Mockus *et al.*, 2000; 2002). In a core-periphery organization, the majority of participants contribute to smaller, localized components in the codebase, while a small group of "core contributors" is responsible for the larger components and the system as a whole. The core contributors generally range throughout the system and frequently communicate with one another to coordinate their activities and arrive at a common vision.

To date there have been no studies attempting to correlate the core-periphery technical architecture of a codebase with a core-periphery organizational structure in the community. In a given project, both might exist, but the organizational structure might not be mapped onto the technical structure as the mirroring hypothesis requires. Nevertheless it is reasonable to hypothesize that core members of a project might be drawn into the technical core of the system. The technical core, by definition, is dense with technical interdependencies; hence, complex problems requiring communication and coordination are likely to arise in its vicinity. As a result, core members of the community pursuing their normal problem-solving and systems integration activities may frequently find themselves working in the technical core even if they do not know exactly where it is.

8. Conclusion

In this article we have attempted to present a comprehensive view of the mirroring hypothesis. The hypothesis predicts that there will (or should) be a correspondence between the dependencies in the technical architecture of a complex system and organizational ties among those responsible for designing or sustaining it. In mirrored organizations, organizational ties that facilitate communication and joint problem-solving are dense where technical problems are most likely to arise. We began by formally defining the hypothesis in terms of a correspondence between two network graphs. We developed descriptive and normative versions of the hypothesis and then reviewed the empirical evidence in industry studies, within and across firms, and in open collaborative projects.

8.1 Overview of results

Studies of industry dynamics showed that, through the economics of mirroring, a radical change in technical architecture can over time reshape the structure of an entire industry. Furthermore, the change in technical architecture might be instigated as a strategic move by a single firm. In other cases, however, most notably the auto industry, attempts by firms to reshape the industry failed because the firms had not accounted for latent technical interdependencies well enough to support the desired shift in firm boundaries and capabilities.

Studies of the dynamics of mirroring also showed that, when the technologies are changing and becoming more complex, dimensions of technical performance are likely to be more interdependent than system designers realize. Knowledge about such systems is *always* incomplete and evolving, and thus firms should purposefully invest in organizational arrangements, practices, and routines that serve to expand their knowledge boundaries beyond their task boundaries. Such "partially mirrored" systems are costlier to sustain than strictly mirrored systems, but they allow firms to avoid premature modularization, respond to architectural innovations arising outside their boundaries, and in some cases initiate architectural innovations to gain competitive advantage.

Studies of buyer–supplier relations and alliances and consortia also showed that it is possible to achieve high levels of technical integration and cooperation across firm boundaries via relational contracts. Such contracts require there to be significant incremental value in a continuing relationship. They become more robust through repeated positive interactions, relationship-specific investments, and shared understanding of the evolving technical system. Significantly, their use was generally motivated by the high costs and capabilities requirements associated with developing exceptionally complex technology. Thus the prevalence of collaboration across firm boundaries is likely to rise as more firms move in this general technological direction.

Finally, new digital technologies have made possible new methods of coordination. Specifically, it is now possible to assemble groups of problem-solvers from around the globe to work interdependently on a common problem for short periods of time. It is also possible for dispersed agents to work asynchronously and without direct communication, coordinating their work stigmergically by interacting with a changing artifact. Lastly, many digital systems have evolved to a dual core-periphery structure in which the technical architecture has a single complex core and peripheral components, while the organization has a core of consistently engaged contributors and a periphery of transient participants. No study has yet looked to see whether the technical and organizational cores in these systems are mirrored: this is an opportunity for future work.

8.2 Boundary conditions on mirroring

On the whole, the mirroring hypothesis captures quite well the central relationship between technical dependencies and organizational ties in complex technical systems both within and across firms. However, when the underlying technologies are rapidly changing and becoming more complex, breaking away from the logic of strict mirroring can lead to better technical performance and competitive advantage. Figure 3 summarizes our view of the boundary conditions applicable to the mirroring hypothesis based on our empirical data. The vertical axis indicates the rate of technical change and growing complexity: as explained above, these features tend to go hand-in-hand. The horizontal axis indicates the composition of the system: does it contain physical components, digital components, or both. (Today as digital technologies diffuse through the economy, the number of digital and mixed systems is growing, and the number of purely physical systems is shrinking.)

In physical and mixed systems, when technologies are relatively stable and complexity is growing slowly, mirroring is a common and generally efficient way to deploy organizational resources to solve technical problems. As the rate of technical change increases and systems become more complex, however, firms taking on the role of systems integrators must have system-wide knowledge extending beyond the tasks they perform in-house. At the same time, architectural innovations outside the boundaries of a given firm become more likely and strict mirroring can become a trap. Partial mirroring is then the recommended strategy.

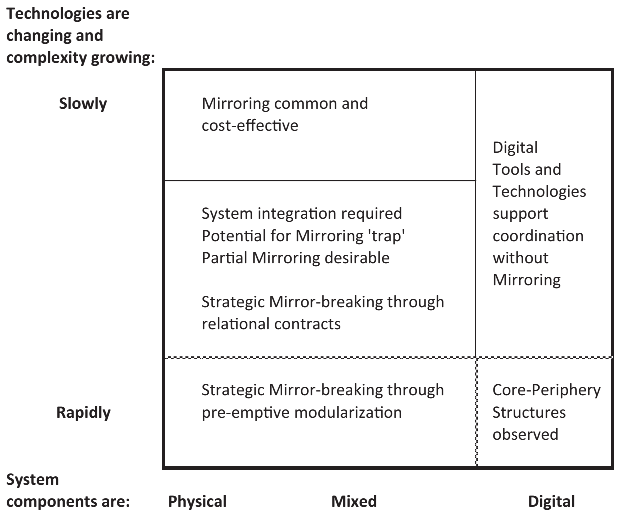

Figure 3. Boundary conditions on the mirroring hypothesis.

Responding to higher rates of technical change and growing complexity of systems, firms may also choose as a matter of strategy to ‘break the mirror’ by investing in relational contracts. In these cases, firms bilaterally or multilaterally seek to foster high levels of communication and cooperation across their boundaries with selected partners. These firms strategically ‘break the mirror’ by increasing technical interdependencies across their boundaries, but do so in the context of a long-term, mutually advantageous relationship.

A less common form of mirror-breaking (in our sample) is for a single firm to create a new, modular technical architecture within its own boundaries. The advantages of modular architectures generally are higher levels of flexibility and adaptability, made possible by lower levels of complexity achieved through information hiding. These advantages enable a firm to drive the rate of technical change in its products and systems to even higher levels (Baldwin and Clark, 2000). Thus firms electing to modularize within their own boundaries are often in highly dynamic technical environments. They may be seeking to pre-empt rivals by increasing the rate of technical change necessary to compete in their product markets.

Digital technologies are shown in the right-hand column. Our sample of open collaborative projects shows that digital tools and technologies can support coordination in ways that go beyond the organizational ties of traditional mirroring. Stigmergic coordination can replace direct communication. High bandwidth communication makes collocation unnecessary. Self-selection and voluntary participation in contests and communities can take the place of formal employment relations. While these new coordination methods were most striking in studies of open collaborative projects, they are no less available to firms today. As digital technologies spread into mixed systems, we expect these methods to diffuse as well.

We also observed core-periphery technical and organizational systems in open collaborative projects, but not in firms. However, core-periphery is the characteristic structure of a platform, which is an increasingly common architecture for systems made up of hardware and software. The core-periphery structure has advantages in that it takes account of different degrees of modularity, interdependence, and cognitive complexity in different parts of a large system and deals with these using different organizational methods. Thus as software becomes more embedded in physical systems, we expect core-periphery structures and corresponding methods of coordination to become widespread.

8.3 Limitations

This study is limited by sample and methodology. In terms of the sample, we cast a wide net by surveying numerous publication outlets, and adding works known to us or brought to our attention. However, it is impossible to construct a truly comprehensive sample. The second limitation lies in the fact that our methods of classification were necessarily subjective and more coarse-grained than the studies themselves. We are only able to describe the most common patterns, not all patterns. A third limitation is that, in the normative studies, successes outnumber failures by a margin of three to one (48 successes to 16 failures). This asymmetry is likely due to scholars' legitimate interest in best practices as found in successful firms. However, it leaves some gaps in the data: for example, we have no cases in which a strategy of partial mirroring was unsuccessful.

8.4 Future work

This study opens up several lines of future research. First, we have seen that when technical systems are changing rapidly and becoming more complex, deviations from the logic of strict mirroring will be beneficial for both firms and groups of firms (ecosystems). In particular, it is advantageous for these firms to draw their knowledge boundaries more broadly than their task boundaries and to consider whether to 'break the mirror' through relational contracts or pre-emptive modularization. How then does a division of labor involving overlapping knowledge shape the evolution of capabilities (Jacobides, 2006; Argyres and Zenger, 2012)? There is evidence in our sample that integrated firms can both initiate and respond to architectural innovations more effectively than specialized firms (Fixson and Park, 2008; Kapoor and Adner, 2012). But such firms can also be blind-sided by new modular architectures or may pursue modularity inappropriately (Baldwin and Clark, 2000; MacDuffie, 2013; Jacobides *et al.*, 2015). From a normative standpoint, how can such firms know when it is advantageous to break the mirror, and when it is foolhardy? Relatedly, what are the limits of modularization as a process: are some end products just too intrinsically interdependent to break apart into modules?

Second, core-periphery technical and organizational structures are becoming more prevalent as many firms are attempting to turn their products into platforms that can attract external complementors. Scholars are beginning to study the organizational changes firms must make to support such strategies, but this work has only just begun (Gawer and Phillips, 2013; Lifshitz-Assaf, 2014; Altman *et al.*, 2014). The relationship between technical dependencies and organizational ties *in platforms* has not yet been addressed and is a promising area for future work. Relatedly, in platforms, how should firms trade-off the flexibility of modular architectures vs. the stability of relational contracts?

Finally, in open collaborative projects, a relatively new organizational form, we have seen that digital technology can support both transient organizational structures and stigmergic coordination. Firms are increasingly adopting these practices both internally and externally. The question then arises: in a digitally connected world, what constitutes an effective organizational tie and what ties are needed to resolve technical dependencies and get work done?

We began this article by noting that innovation is a process of defining problems and developing knowledge needed to solve them effectively. The mirroring of technical interdependencies and organizational ties is a solution to the problem of managing complex technical systems while conserving scarce cognitive resources. Mirroring has benefits, thus not surprisingly, it is a prevalent pattern in the economy at large. But it also has costs, especially when the underlying technology is dynamic and complex and architectural innovation a likely possibility. Digital tools and technologies also give rise to new patterns including transient mirroring, stigmergic coordination, and core-periphery structures. As digital technology diffuses, we expect these new patterns to become more common. Our study thus captures mirroring at a time of transition: from the stable architectures and closed organizations of the past to increasingly dynamic architectures and open, evolving organizational ecosystems in the future.

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